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AN ECONOMIC AND PERFORMANCE DESIGN STUDY OF SOLAR PREHEATERS FOR DOMESTIC HOT WATER HEATERS IN NORTH CAROLINA

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16. Abstract

A study of the performance and estimated material costs for several solar preheaters for domestic hot water heaters using isolation levels present in North Carolina is carried out. The study includes the effects of monthly variations in isolation and the direction of incident radiation. Demand is assumed at 13 gallons (49.2 liters) per day per person. The study shows that a closed circulation system with 82 gallons (310 liters) of preheated storage and 53.4 ft^2 (4.94 m^2) of collector surface with single cover can be expected to cost about $800 and to repay it capital cost and interest (at 8%) in 5.2 years, assuming present electric rates increase at 5% per year.

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INTRODUCTION

With the emergence of the energy crisis in the United States, alternative energy sources are being investigated seriously in hopes of reducing America's dependence on foreign supplies of fossil fuels. A great deal of this attention has been directed toward utilization of solar energy for large scale power production as well as for the more typical applications of heating buildings and providing domestic hot water. While extensive research and development is needed before solar energy sources can be expected to assume a significant portion on the total U. S. Energy burden, it has been demonstrated that present day methods and materials are adequate to produce low-grade hot water suitable for a variety of uses. In the past, the high initial expenditures required for solar energy collection all but eliminated its use in a competive market. However, in light of escalating fuel costs, solar energy utilization is becoming more and more attractive and represents a realistic alternative to fossil fuels. It is the purpose of this report to explore the merits of utilizing solar energy to provide domestic hot water with an emphasis on systems and construction methods suitable for assembly and installation by the homeowners of North Carolina.

Domestic hot water production, in contrast to solar space heating, warrants particular attention for early development for several important reasons. The systems are generally of a relatively small scale and are used throughout the year, resulting in a more cost effective unit than most space heating designs (unless, perhaps, solar cooling is also specified). Additionally, the designs are also relatively simple and can usually be constructed with stock materials by a talented, but not necessarily professional, handyman. Domestic hot water systems are equally suited in a retrofit capacity as well as for new construction. These factors, coupled with the enthusiastic response of the public at the solar energy exhibit during the N. C. Fair, suggest that widespread installation of solar water heating would result if adequate design information and guidance were available.

SOLAR AVAILABILITY AND SELECTION OF COLLECTOR TILT ANGLE

Monthly averages of daily solar radiation data collected in Greensboro, N. C. by the U. S. Weather Service over a period of seven years are shown in Table 1. The figures indicate the total energy received on a south-facing surface in units of BTU/ft^2 (1.A) and KWH/m^2 (1.B). Using methods suggested by J. A. Duffie and W. A. Beckman[1], the radiation received by a tilted surface was calculated for various angles of tilt. The total radiation was assumed to be composed of 61% beam and 39% diffuse radiation components. The small difference in average values for the different angles results from the fact

[1]Duffie, J. A. and W. A. Beckman; Solar Energy Thermal Processes. (New York, 1974).

TABLE 1.A

Mean Daily Solar Insolation for a South Facing Surface at Various Tilt Angles+ (BTU/ft^2)
Location: Greensboro, North Carolina ∿ 36.5°N. Lat.

Month	Title Angle					Optimum Angle
	Horz	25°	36.5°	42°	55°	
January	737	1007	1086	1112	1147	58.5°
February	1018	1260	1320	1346	1347	49°
March	1305	1503	1533	1480	1494	39°
April	1729	1851	1834	1809	1709	26.5°
May	1958	2014	1960	1917	1776	18.5°
June	2080	2090	2011	1957	1761	13.5°
July	2006	2025	1953	1902	1743	14.5°
August	1788	1876	1843	1809	1693	22.5°
September	1497	1667	1678	1667	1603	33.5°
October	1187	1430	1482	1493	1481	45.5°
November	895	1169	1245	1268	1291	54.5°
December	726	1003	1087	1115	1152	59.5°
Average	1412	1575	1585	1573	1516	36.25°

+ From data collected by U. S. Weather Bureau.
By methods described by Duffie and Beckman in Solar Energy Thermal Processes.
Assuming 0 ground reflectance and 61% beam radiation component.

that only collection of the beam radiation component is effected by the collector tilt. The optimum tilt angle for each month is also shown. While a solar hot water heating device is used throughout the year, collection is more difficult during the winter months due to lower ambient temperatures and it is felt that wintertime efficiency should be stressed more heavily. Consideration of this fact and the data shown above lead to the selection of a collector tilt angle of 55° for use in the calculations that follow in this report.

TABLE 1.B

Mean Daily Solar Insolation for a South Facing Surface at Various Tilt Angles+ (KWH/m^2)
Location: Greensboro, North Carolina ∿ 36.5° N. Lat.

Month	Title Angle					Optimum Angle
	Horz	25°	36.5°	42°	55°	
January	2.32	3.17	3.42	3.50	3.61	58.5°
February	3.21	3.97	4.16	4.24	4.24	49°
March	4.11	4.74	4.83	4.66	4.71	39°
April	5.45	5.83	5.78	5.70	5.38	26.5°
May	6.17	6.35	6.18	6.04	5.59	18.5°
June	6.56	6.59	6.34	6.17	5.55	13.5°
July	6.32	6.38	6.16	5.99	5.49	14.5°
August	5.64	5.91	5.78	5.70	5.33	22.5°
September	4.72	5.25	5.29	5.25	5.05	33.5°
October	3.74	4.50	4.67	4.70	4.67	45.5°
November	2.82	3.68	3.92	3.99	4.07	54.5°
December	2.29	3.16	3.43	3.51	3.63	59.5°
Average	4.45	4.96	5.00	4.95	4.78	36.25°

+ From data collected by U. S. Weather Bureau.
By methods described by Duffie and Beckman in Solar Energy Thermal Processes.
Assuming 0 ground reflectance and 61% beam raidation component.

BASIC HOT WATER SYSTEM LAYOUTS

Numerous solar hot water heating schemes have been developed to meet various design requirements as determined by the locality, the availability and cost of materials, and the degree of mechanical sophistication desired. A reliance on auxiliary energy is necessary in nearly all systems since costly over-designing of collector area and storage volume would be required to provide energy for 100% of the hot water demand. Thus, units may range from small pre-heaters to systems which assume a majority of the heating load and the selection of the most suitable design for a particular application becomes a problem of cost-effective optimization. The cost analyses of some specific designs are presented later in this report.

System layouts and a discussion of the relative advantages and disadvantages of several designs follow:

I. DIRECT CIRCULATION SYSTEM (SEE FIGURE 1)

In this system water from the city line or well is circulated directly through a solar collector prior to entering a typical hot water tank where auxiliary heat is provided as required.

A. Advantages

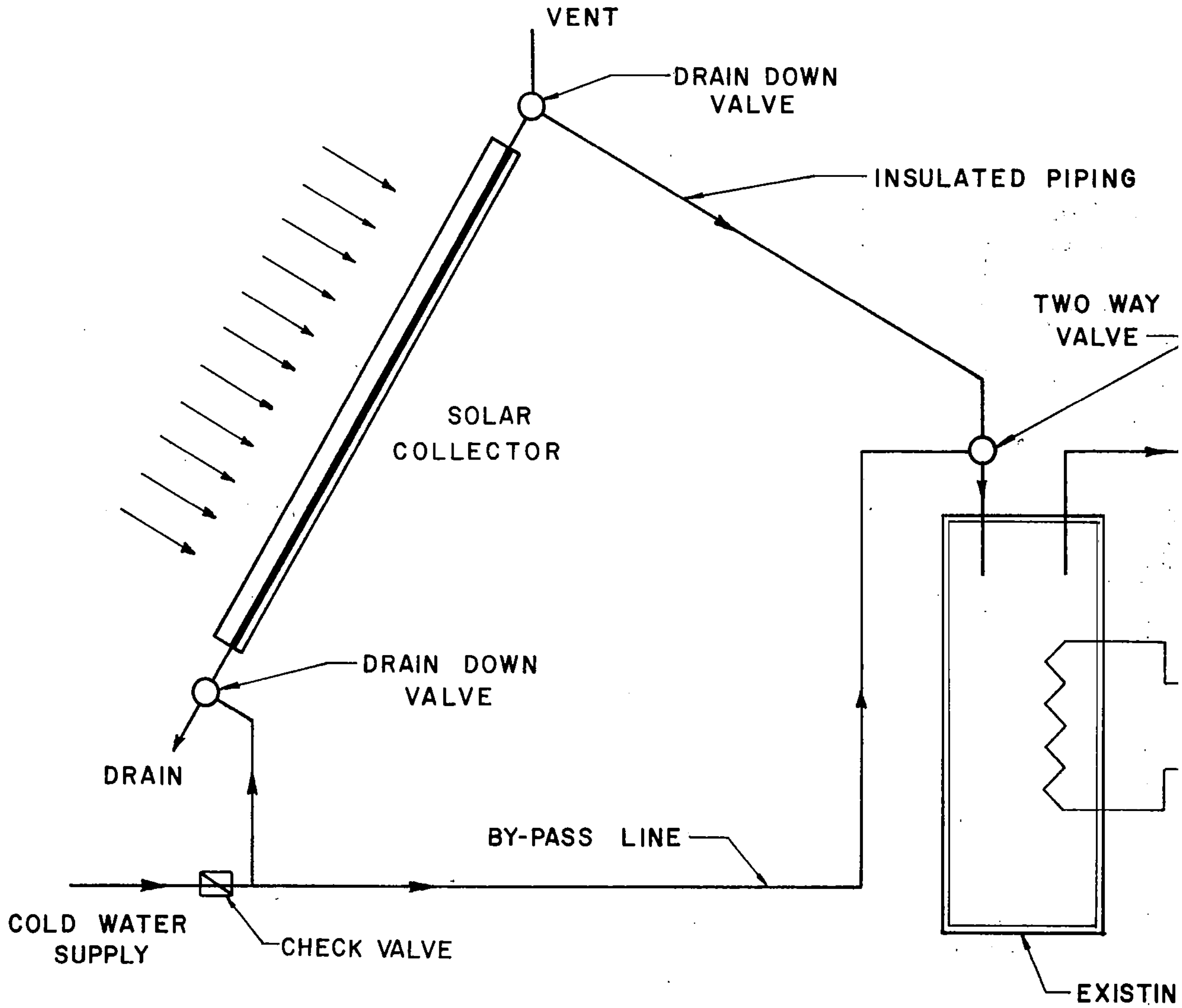
1. A very simple and inexpensive design.
2. No pump or controls necessary (controls needed in freezing climates).
3. Low maintenance.

B. Disadvantages

1. Inefficient. Collector only in use when hot water is drawn from tap.
2. No storage capability.
3. Flow tubes in collector must be constructed of materials not corroded by water.
4. Drain down provision must be provided for freezing climates. Additional controls and piping required.

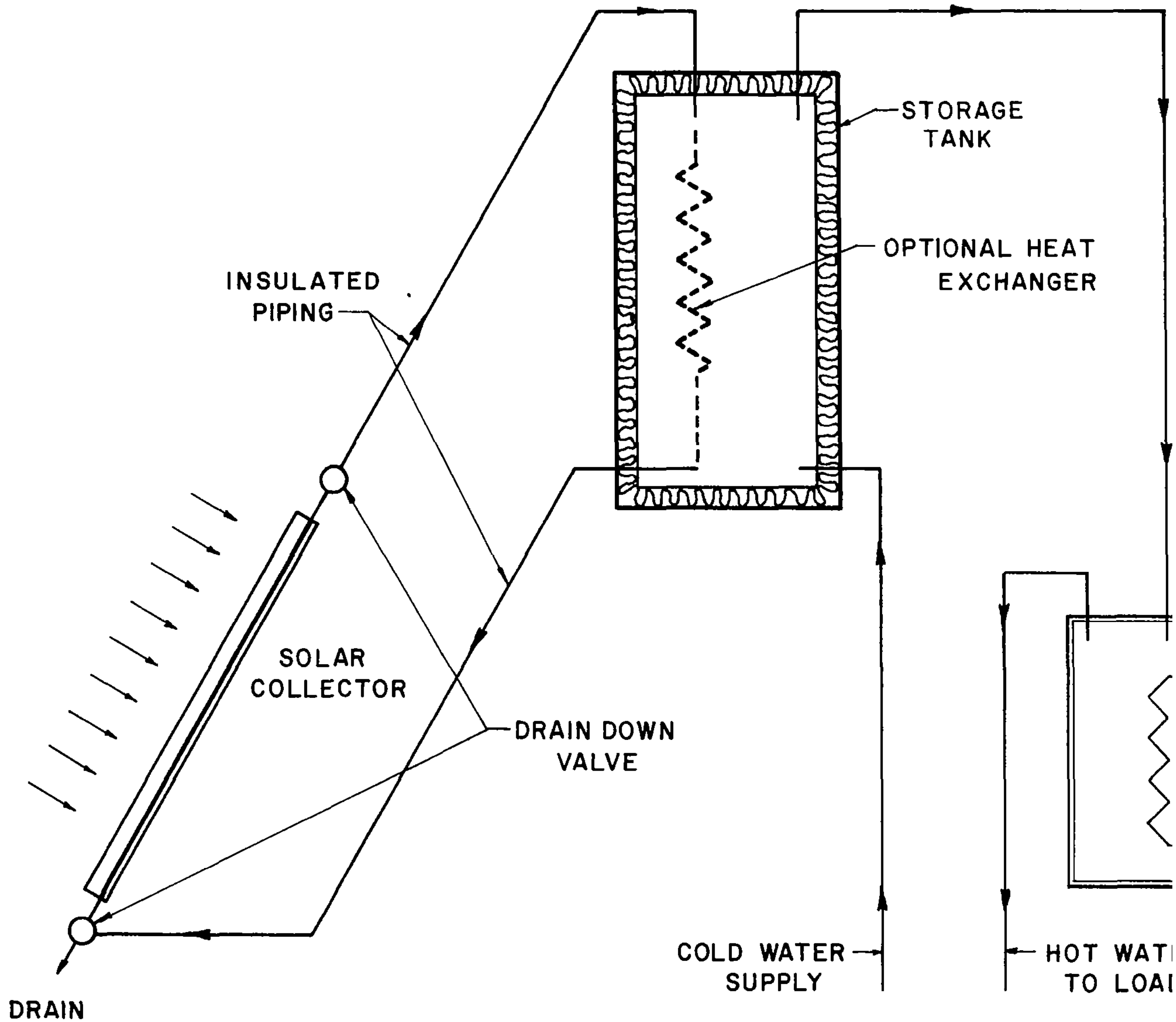
II. THERMOSIPHON SYSTEM (SEE FIGURE 2)

In the thermosiphon system a storage tank is mounted above the collector and natural circulation of the working fluid results when the density of the fluid in the collector is lowered as it is heated by the sun. A fluid other than water may be used if a suitable heat exchanger is located in the storage tank. Auxiliary heat may be provided in the storage tank or, more preferably, in a small tank after the pre-heated water leaves the storage area (the existing hot water tank in a retrofit design).



DIRECT CIRCULATION SYSTEM

Figure 1



THERMOSIPHON SYSTEM

Figure 2

A. Advantages

1. Relatively simple design.
2. No pump required.
3. Anti-freeze solution may be used if a heat exchanger is mounted in the tank.

B. Disadvantages

1. Tank must be mounted above the collector.
2. Low flow rates result in less efficient collection than forced circulation.

III. OPEN CIRCULATION SYSTEM (SEE FIGURE 3)

In an open circulation system water is circulated from the storage tank to the solar collectors. A differential temperature relay switch actuates the pump when the collector temperature is a prescribed amount higher than the tank temperature.

A. Advantages

1. Collectors may be mounted above the storage tank.
2. Make up water is circulated directly through the collectors resulting in relatively high system efficiencies.

B. Disadvantages

1. Flow tubes in collector must be of material not corroded by water.
2. Drain down provision must be included in freezing climates.

IV. CLOSED CIRCULATION SYSTEM (SEE FIGURE 4)

The closed circulation system is essentially the same as the open system with the exception of a heat exchanger in the storage tank. The working fluid is circulated in a closed loop from the collector to the heat exchanger which permits the use of a non-corrosive anti-freeze solution.

A. Advantages

1. Freeze protection provided without drainage of collector.
2. Less expensive materials may be used for collectors since water is not the working fluid.

B. Disadvantages

1. Additional heat exchanger required.
2. Initial cost and maintenance of working fluid.
3. Less efficient due to temperature drop across heat exchanger.
4. Possible safety code complications unless a non-toxic working fluid is utilized.

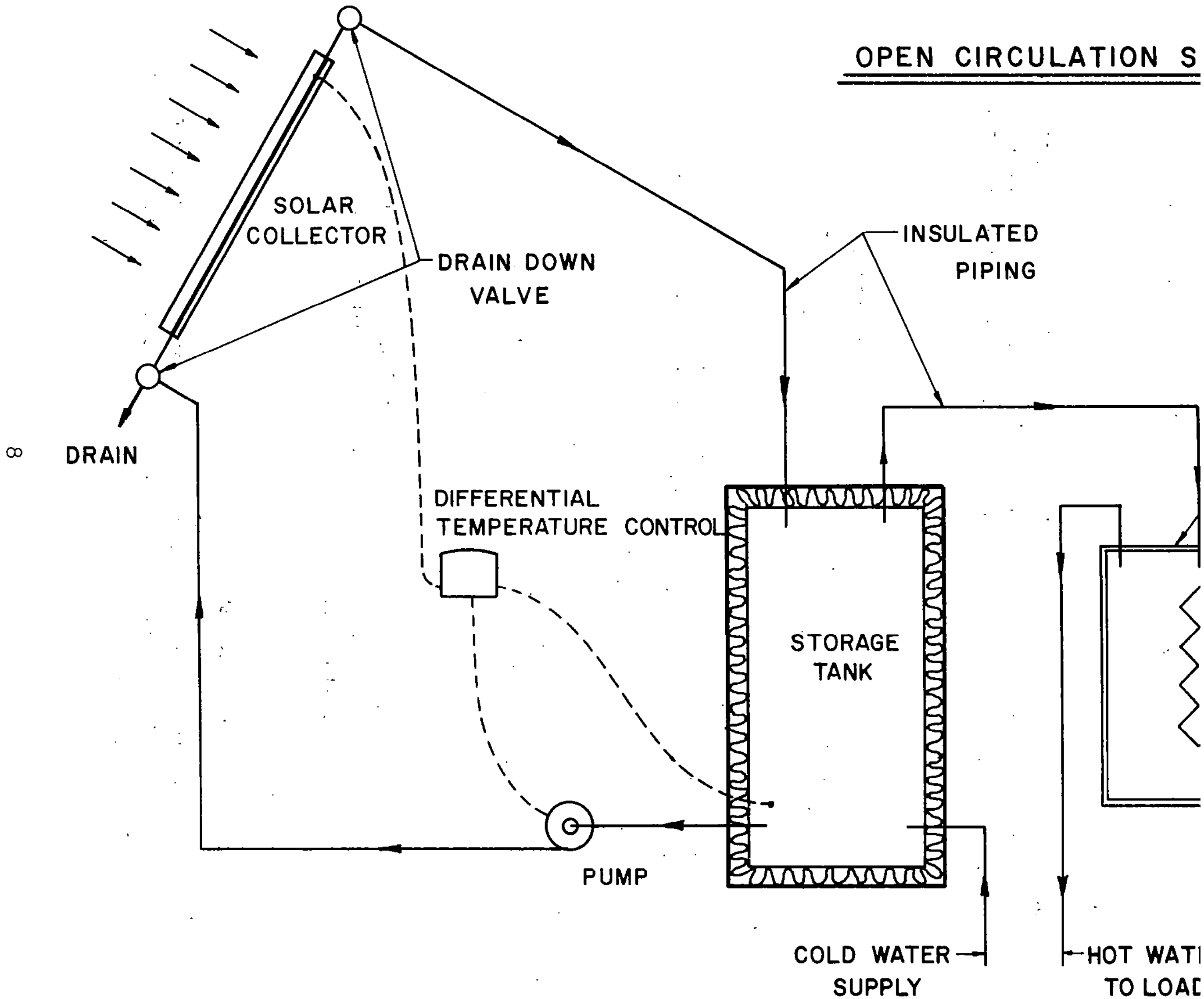
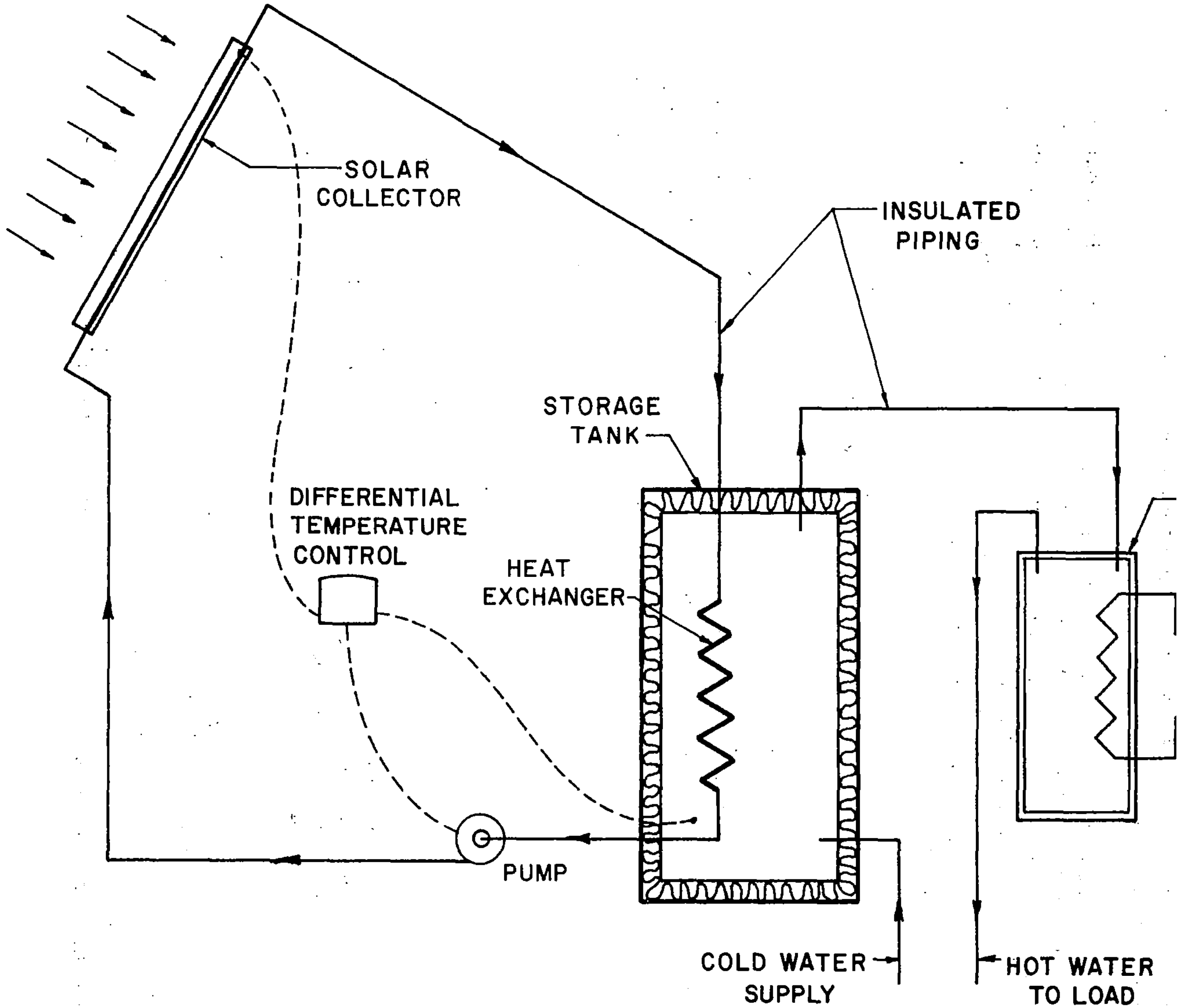

OPEN CIRCULATION S
SOLAR
COLLECTOR
DRAIN DOWN
VALVE
INSULATED
PIPING
DRAIN
DIFFERENTIAL
TEMPERATURE CONTROL
STORAGE
TANK
PUMP
COLD WATER
SUPPLY
HOT WAT
TO LOA

Figure 3



CLOSED CIRCULATION SYSTEM

Figure 4

FLAT PLATE COLLECTORS

The solar collection system is the most important and costly component in a solar energy design. While many new configurations are currently being investigated, discussion in this report is restricted to flat plate, liquid type solar collectors. It is recognized that focusing collectors, for instance, can generate higher temperatures, but it is felt that for a domestic hot water system the flat plate provides adequate performance and is the simplest and most cost-effective option.

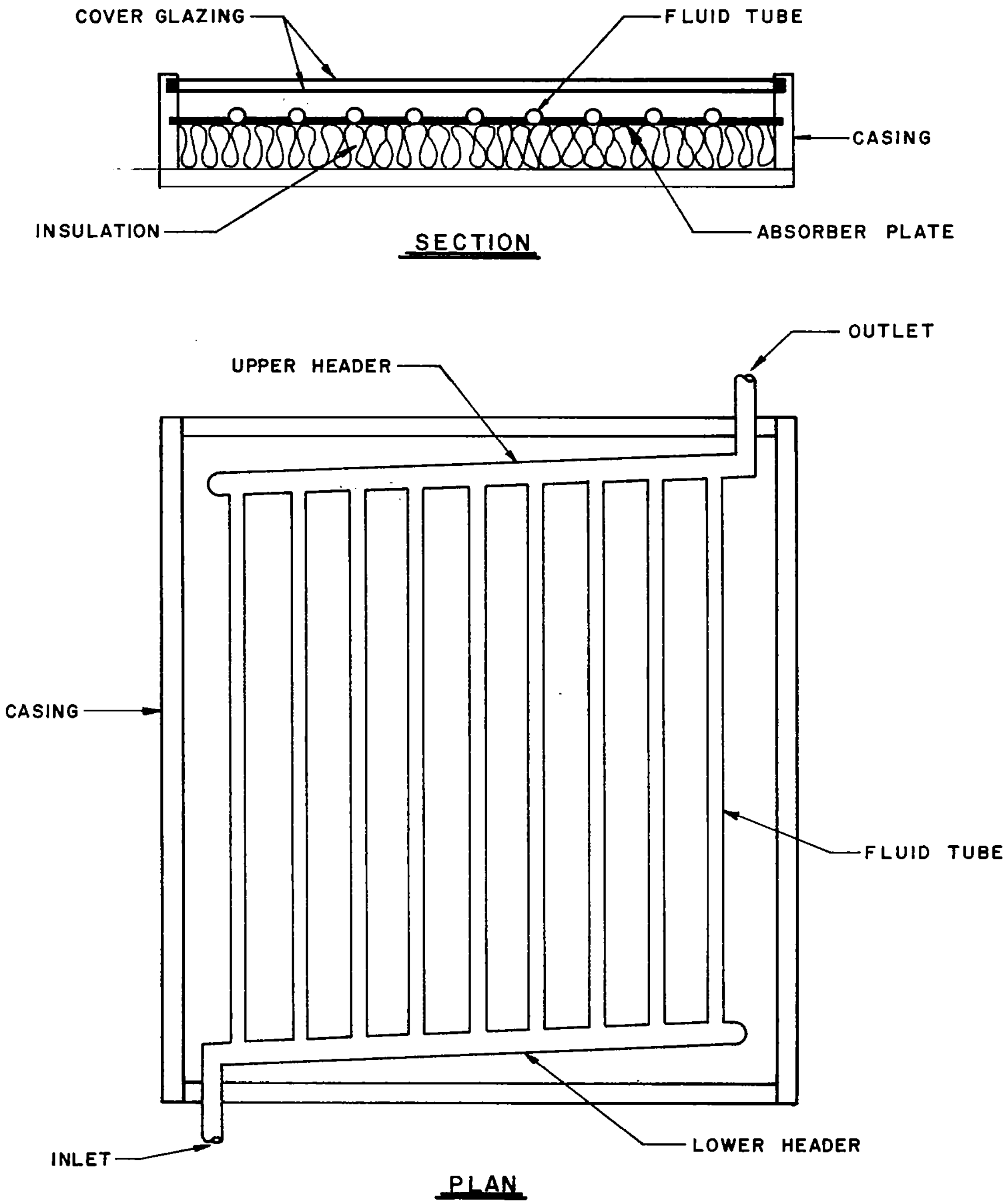
A plan and cross section of a typical flat plate collector is shown in Figure 5. The cover system, insulation, and collection housing may all be revised to provide a more efficient or less expensive unit. However, the greatest design flexibility exists with regard to the absorber plate itself. Numerous construction techniques and material alternatives are available to enable the engineer to design what he feels to be the most suitable combination for the particular application.

Figure 6(a) shows an absorber plate to which the flow tubes are either mechanically bonded or soldered. This type involves considerable labor and expertise, especially if the plate and tubes are of dissimilar materials (composite construction). Resistance to heat conduction at the bond may also be a problem if it should deteriorate due to weathering or thermal stress. The flow passages in the absorber plate shown in Figure 6(b) are an integral part of the plate material. This construction technique, developed by Olin Brass and known as Roll Bond, has the advantage of low manufacturing cost (little labor is required to produce even complicated flow arrangements) and efficient heat transfer properties. A disadvantage is that the plate must be composed of only one material, the most common being copper, aluminum, or steel.

Figure 6(c) illustrates a "waffle" type absorber plate on which the joints are spot welded. This design provides excellent heat transfer capability, but is higher in production costs than the collectors described above.

An open channel flow design is shown in Figure 6(d). Although this design is attractive from the standpoint of simplicity, it results in lower efficiencies due to reflective losses from the fluid surface and also from chemical impurities which may be deposited by the working fluid. Plastic "bag" absorbers are currently being produced commercially, but limited life expectancy due to ultraviolet deterioration is a major drawback and reduces their applicability.

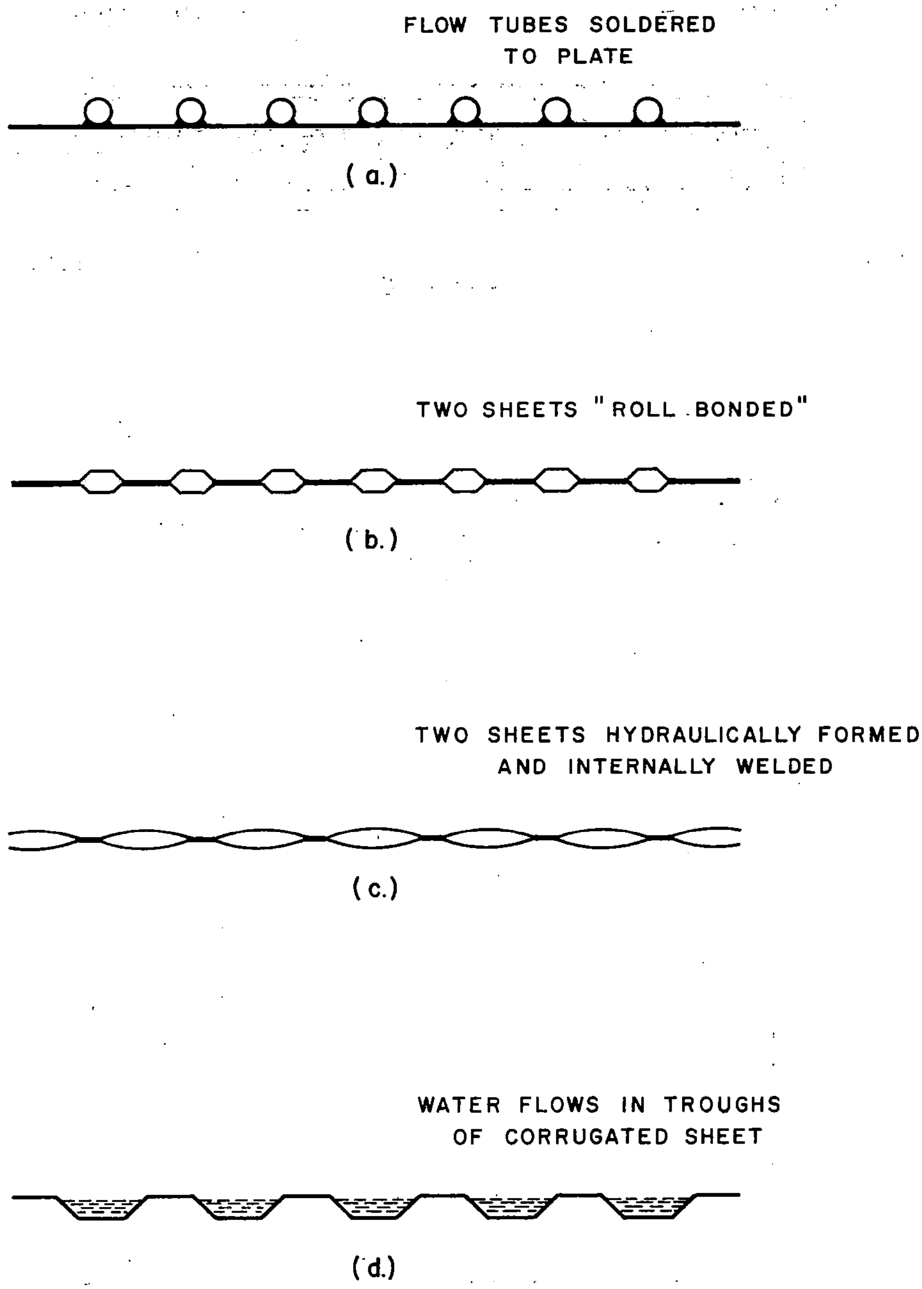
Material selection for an absorber plate is generally a function of its heat conductivity, cost, availability, ease of tooling, and compatibility with other system components, particularly the working fluid. If tap water is circulated directly through the collector, corrosion becomes a major problem and copper or stainless steel flow passages are generally required. Unless composite construction is specified, the resulting material costs are very



TYPICAL FLAT PLATE SOLAR COLLECTOR

NOT TO SCALE

Figure 5



ABSORBER PLATE VARIATIONS

Figure 6

high. However, as noted above, the high production costs and other disadvantages of composite construction must not be overlooked.

If it is decided to utilize a closed circulation system with a non-corrosive working fluid, the material selection is greatly simplified. In this instance, the best solution seems to be an aluminum Roll Bond absorber which possesses low cost, high thermal conductivity, and light weight.

One interesting alternative to the collectors described above is a glass or plastic tube arrangement through which a "blackened" working fluid is circulated and absorbs the incident radiation directly. Although this type device is still under development, indications are that it possesses comparable efficiencies to the more conventional collectors mentioned above.

The overall efficiency of a solar collector is sensitive to a variety of operational parameters as well as the design options employed. As one might expect, higher efficiencies generally imply higher costs, but it is felt that a mean efficiency of 50% can be expected under normal operating conditions without the use of such sophisticated materials as etched cover plate glass and optically selective absorber coatings. Investigation of collectors currently available and of comprehensive studies on collector design and performance suggest that a Roll Bond aluminum collector can be produced for $4 to $5 per square foot ($43 to $54 per square meter) while an all-copper collector (Roll Bond) would cost about $10 to $11 per square foot ($108 to $118 per square meter). It is recognized that these figures are subject to variation, but are reasonable values for use in a cost analysis at the present time.

THERMAL STORAGE AND CONTROLS

Of the thermal storage alternatives available to the designer, water storage appears to be the most desirable for a domestic water heating unit. Although determination of optimum storage volume for a particular design is a complicated matter at best, a general rule of thumb is about 10 to 15 pounds of water for every square foot of collector area (48.8 to 73.2 kg/m^2). The tank should be well insulated and constructed of a corrosion-resistant material. When an open circulation system is used, there need be no provision for an internal heat exchanger and a modified, glass lined (or equivalent) tank would be suitable. The need for a heat exchanger in the closed circulation system requires a more expensive unit.

Controls for the solar water heater are relatively simple, but do vary with the type of system employed. The major component of a forced circulation unit is the differential temperature sensor which compares the collector temperature to the tank temperature and activates the pump accordingly. Additional valves are necessary if a drain down capability is required to prevent freeze damage in water circulation systems.

COST ANALYSIS

In an effort to determine the economic feasibility of solar hot water heating in North Carolina a cost analysis was performed on three of the basic systems described above. The estimated initial costs were amortized over an expected minimum lifetime of 15 years. The interest rate was taken to be 8%. As shown in elementary economic texts the initial capital cost may be expressed on an annual basis by the equation

$$C_A = C_I \cdot CRF$$

where C_A = annual cost of solar system neglecting operating costs in \$/yr.
C_I = total initial investment, \$.
CRF = Capital recovery factor, \$/\$/yr.

and

$$CRF = \frac{i_d(1 + i_d)^t}{(1 + i_d) - 1}$$

where i_d = annual interest rate, \$/\$/yr.
t = expected lifetime.

For the assumed values of i_d and t stated above CRF = 0.1168. If one wishes to determine the cost effectiveness of a solar system with increasing energy cost, an effective interest rate may be approximated by the equation

$$i_{eff} = \frac{1 + i_d}{1 + j}$$

where i_{eff} = effective interest rate with fuel price escalation.
i_d = annual interest rate.
j = rate of energy price escalation.

The maximum economically justifiable investment (break even) in a system may be computed (with the effective interest rate) as a function of the present savings in energy costs realized by use of the solar water heating unit. Table II shows the results of this computation for various combinations of system lifetimes, interest rates, and projected energy cost increase rates.

TABLE II

Economically Justifiable Investment in Solar-Heating Systems for Each Dollar per Month ($12/yr) in Present Savings

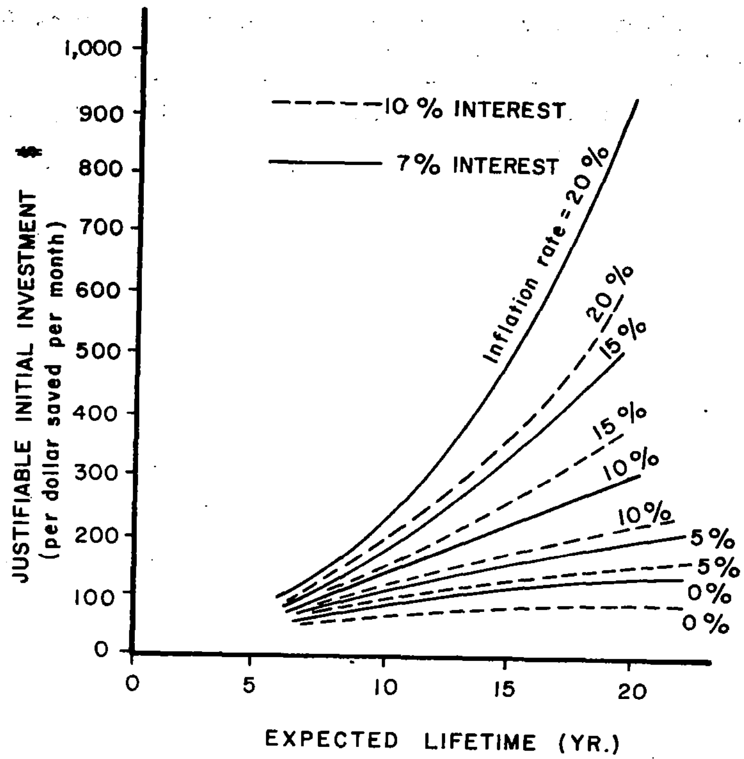
Projected system lifetime, yr	Projected fuel cost increase, %/yr	Interest rate, %/yr		
		7	10	12
	0	50.76	47.54	45.59
	5	56.98	53.21	50.94
5	10	63.91	59.53	56.88
	15	71.62	66.54	63.47
	20	80.18	74.30	70.77
	0	86.95	77.06	71.46
	5	108.83	95.38	87.82
10	10	137.30	119.05	108.86
	15	174.33	149.63	135.91
	20	222.42	189.11	170.70
	0	112.76	95.38	86.13
	5	156.01	128.80	114.54
15	10	221.56	178.58	156.36
	15	321.62	253.41	218.59
	20	474.79	366.49	311.79
	0	131.16	106.77	94.46
	5	198.95	155.28	133.89
20	10	318.33	238.10	199.77
	15	532.84	383.02	312.95
	20	922.51	640.55	510.99

In Figure 7 the same results are shown in graphical form for interest rates of 7% and 10%[2].

The pay off period for a solar energy system may be calculated from the equations shown above by letting the annual cost equal the present yearly savings and solving for t. Thus,

$$t = \frac{\ln\left(\dfrac{C_A}{C_A - i_{eff}C_I}\right)}{\ln(1 + i_{eff})}$$

[2] Kreider, J. F. and F. Kreith; Solar Heating and Cooling. (Wash., D. C., 1975) pg. 124-128.



10 % INTEREST
7% INTEREST
Inflation rate = 20 %
20 %
15 %
15 %
10 %
10 %
5 %
5 %
0 %
0 %
JUSTIFIABLE INITIAL INVESTMENT $
(per dollar saved per month)
1,000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
EXPECTED LIFETIME (YR.)

Figure 7

1. DIRECT CIRCULATION SYSTEM

In a direct circulation system the collector may only be utilized during periods of actual hot water demand. A typical daily demand curve, expressed as an hourly step function, is shown in Figure 8(a) based on an average consumption of 13 gallons (49.2 liters) per day per person. Figures 8(b) and 8(c) show the available solar energy in Greensboro at a tilt angle of 55 degrees during the months of June and December, respectively. Given an inlet water temperature, T_1, the energy necessary to heat a quantity of water to a required output temperature, T_2, may be found by the equation

$$q = mc_p(T_2 - T_1)$$

where q = energy required,
c_p = specific heat of water = 1 BTU/lb °F. (1 cal/g °C)
m = mass of water

Assuming an inlet temperature of 50° F (10° C) and an output temperature of 140° F (60°C) the energy requirement for each hour for a family of four (52 gal/day; 197 liters/day) was computed. A commercially available, all copper absorber, solar collector of an assumed mean efficiency of 50% and an area of 16.2 square feet (1.5 m^2) was used in the analysis. In Table III a summary is shown of the hourly distribution of hot water demand and the abiliy of one to four collector panels to supply the energy necessary during the months of June and December. The significant figures are the total auxiliary energy requirements for the different collector areas. With the results shown in Table III, a life cycle cost analysis was performed; a summary follows:

DIRECT CIRCULATION SYSTEM

(a) Daily demand for 4 persons ∿ 52 gallons (197 liters).
(b) Energy requirement @ 90°F ΔT ∿ 39,000 BTU/day (11.42 KWH/day).
(c) Energy cost @ 4.31¢/KWH. ∿ \$12.63/10^6 BTU.

Number of panels	1	2	3	4
Aux. energy required (average) BTU/day	27,404	21,724	19,500	18,200
KWH/day	8.024	6.361	5.710	5.329
Energy supplied by solar system BTU/day	11,596	17,276	19,500	20,800
KWH/day	3.395	5.058	5.710	6.090
% energy supplied	29.7%	44.3%	50%	53.3%

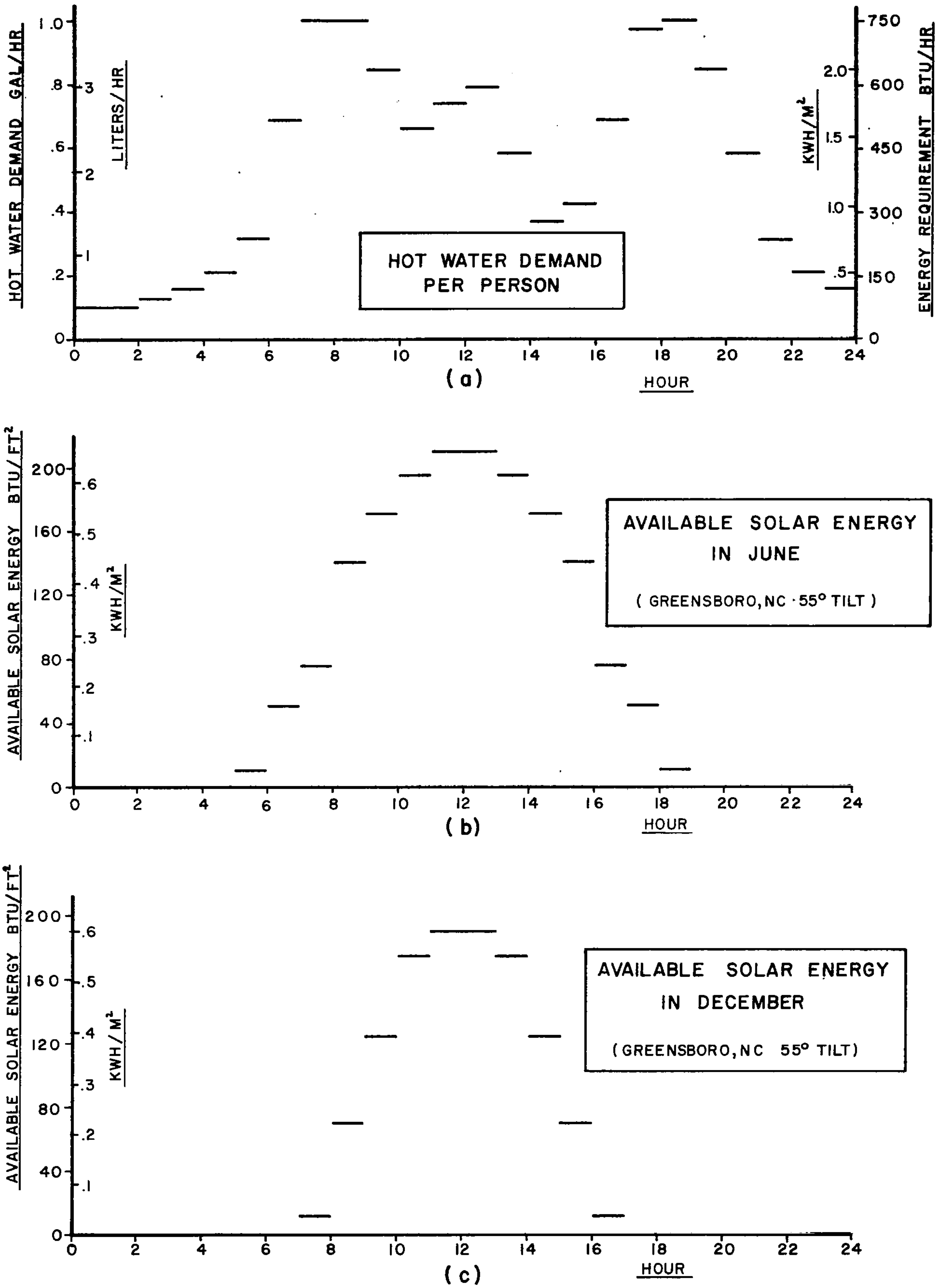

HOT WATER DEMAND GAL/HR
LITERS/HR
KWH/M²
ENERGY REQUIREMENT BTU/HR
HOT WATER DEMAND
PER PERSON
HOUR
(a)
AVAILABLE SOLAR ENERGY BTU/FT²
KWH/M²
AVAILABLE SOLAR ENERGY
IN JUNE
(GREENSBORO, NC · 55° TILT)
HOUR
(b)
AVAILABLE SOLAR ENERGY BTU/FT²
KWH/M²
AVAILABLE SOLAR ENERGY
IN DECEMBER
(GREENSBORO, NC 55° TILT)
HOUR
(c)

Figure 8

TABLE III.A

Hourly Distribution of Hot Water Demand and Direct Circulation System Performance (English Units)

Hour	Hot water demand per person (gal)	Energy required for 4 persons 90°F ΔT (BTU)	Available solar energy (BTU/ft²)		Solar energy collected (BTU) per panel (16.2 ft²) Panel efficiency = 50%	
			June	Dec	June	Dec
12-1	.106	318				
1-2	.106	318				
2-3	.132	397				
3-4	.159	478				
4-5	.211	634				
5-6	.317	952	11.5		93	
6-7	.687	2044	51		413	
7-8	1.004	3016	77	12	624	97
8-9	1.004	3016	141	69	1142	559
9-10	.845	2538	171	124	1385	1004
10-11	.661	1986	194	173	1571	1401
11-12	.704	2223	211	190	1709	1539
12-13	.793	2382	211	190	1709	1539
13-14	.581	1745	194	173	1571	1401
14-15	.370	1111	171	124	1385	1004
15-16	.423	1271	141	69	1142	559
16-17	.687	2064	77	12	624	97
17-18	.978	2938	51		413	
18-19	1.004	3016	11.5		93	
19-20	.845	2538				
20-21	.581	1745				
21-22	.317	952				
22-23	.211	634				
23-24	.159	478				

TABLE IIIA (CON'T.)

Hour	Auxiliary energy required (BTU)							
	1 panel		2 panels		3 panels		4 panels	
	June	Dec	June	Dec	June	Dec	June	Dec
12-1	318	318	318	318	318	318	318	318
1-2	318	318	318	318	318	318	318	318
2-3	397	397	397	397	397	397	397	397
3-4	478	478	478	478	478	478	478	478
4-5	634	634	634	634	634	634	634	634
5-6	859	952	766	952	673	952	580	952
6-7	1651	2044	1238	2044	825	2044	412	2044
7-8	2392	2919	1768	2822	1144	2725	520	2628
8-9	1874	2457	732	1898	0	1339	0	780
9-10	1153	1534	0	530	0	0	0	0
10-11	415	585	0	0	0	0	0	0
11-12	514	684	0	0	0	0	0	0
12-13	673	843	0	0	0	0	0	0
13-14	174	344	0	0	0	0	0	0
14-15	0	107	0	0	0	0	0	0
15-16	129	712	0	153	0	0	0	0
16-17	1440	1967	816	1870	192	1773	0	1676
17-18	2525	2938	2112	2938	1699	2938	1286	2938
18-19	2923	3016	2830	3016	2737	3016	2644	3016
19-20	2538	2538	2538	2538	2538	2538	2538	2538
20-21	1745	1745	1745	1745	1745	1745	1745	1745
21-22	952	952	952	952	952	952	952	952
22-23	634	634	634	634	634	634	634	634
23-24	478	478	478	478	478	478	478	478
Total	25,214	29,594	18,754	24,695	15,762	23,239	13,934	22,466
Yearly average	27,404		21,724		19,500		18,200	

TABLE III.B

Hourly Distribution of Hot Water Demand and Direct Circulation System Performance (Metric Units)

Hour	Hot water demand per person (liters)	Energy required for 4 persons 50°C ΔT (KWH)	Available solar energy (KWH/m^2) June	Available solar energy (KWH/m^2) Dec	Solar energy collected (KWH) per panel ($1.5\ m^2$) Panel efficiency = 50% June	Solar energy collected (KWH) per panel ($1.5\ m^2$) Panel efficiency = 50% Dec
12-1	.401	.0931				
1-2	.401	.0931				
2-3	.500	.116				
3-4	.602	.140				
4-5	.799	.186				
5-6	1.120	.279	.0362		.0272	
6-7	2.600	.598	.161		.121	
7-8	3.800	.883	.243	.0378	.183	.0284
8-9	3.800	.883	.444	.217	.334	.164
9-10	3.198	.743	.539	.391	.406	.294
10-11	2.502	.582	.611	.545	.460	.410
11-12	2.665	.651	.665	.599	.500	.451
12-13	3.001	.697	.665	.599	.500	.451
13-14	2.200	.511	.611	.545	.460	.410
14-15	1.400	.325	.539	.391	.406	.294
15-16	1.601	.372	.444	.217	.334	.164
16-17	2.566	.604	.243	.0378	.183	.0284
17-18	3.701	.860	.161		.121	
18-19	3.800	.883	.0362		.0272	
19-20	3.198	.743				
20-21	2.199	.511				
21-22	1.200	.279				
22-23	.799	.186				
23-24	.602	.140				

TABLE IIIB (CON'T)

Hour	Auxiliary energy required (KWH)							
	1 panel		2 panels		3 panels		4 panels	
	June	Dec	June	Dec	June	Dec	June	Dec
12-1	.0931	.0931	.0931	.0931	.0931	.0931	.0931	.0931
1-2	.0931	.0931	.0931	.0931	.0931	.0931	.0931	.0931
2-3	.116	.116	.116	.116	.116	.116	.116	.116
3-4	.140	.140	.140	.140	.147	.147	.147	.147
4-5	.186	.186	.186	.186	.186	.186	.186	.186
5-6	.252	.279	.224	.279	.197	.279	.170	.279
6-7	.483	.598	.362	.598	.242	.598	.121	.598
7-8	.700	.855	.518	.826	.335	.798	.152	.769
8-9	.549	.719	.214	.556	0	.392	0	.228
9-10	.338	.449	0	.155	0	0	0	0
10-11	.122	.171	0	0	0	0	0	0
11-12	.150	.200	0	0	0	0	0	0
12-13	.197	.244	0	0	0	0	0	0
13-14	.0509	.101	0	0	0	0	0	0
14-15	0	.0313	0	0	0	0	0	0
15-16	.0378	.208	0	.0448	0	0	0	0
16-17	.422	.576	.239	.548	.0562	.519	0	.491
17-18	.739	.860	.618	.860	.497	.860	.377	.860
18-19	.856	.883	.829	.883	.801	.883	.774	.883
19-20	.743	.743	.743	.743	.743	.743	.743	.743
20-21	.511	.511	.511	.511	.511	.511	.511	.511
21-22	.279	.279	.279	.279	.279	.279	.279	.279
22-23	.186	.186	.186	.186	.186	.186	.186	.186
23-24	.140	.140	.140	.140	.140	.140	.140	.140
Total	7.383	8.665	5.491	7.231	4.615	6.804	3.922	6.578
Yearly average	8.024		6.361		5.710		5.329	

COLLECTOR SYSTEM COST

Collector cost = \$10.50/ft^2 (\$113.00/m^2)

Collector area = 16.2 ft^2/panel (1.5 m^2/panel)

Panel cost = \$10.50/ft^2 x 16.2 ft^2 = \$170/panel

Valves, piping and controls cost = \$150.00

Lifetime - 15 years

Interest rate - 8%

(a) <u>One panel system</u>

System cost = \$170.00 + \$150.00 = \$320.00
Capital recovery factor (15 yrs @ 8%) = 0.117
Annual cost = \$320.00 x 0.117 = \$37.44/year

(b) <u>Two panel system</u>

System cost = 2(170.00) + 150 = \$490.00
Annual cost = (\$490)(0.117) = \$57.33/year

(c) <u>Three panel system</u>

System cost = 3(170.00) + 150 = \$660.00
Annual cost = (\$660)(0.117) = \$77.22/year

(d) <u>Four panel system</u>

System cost = 4(170.00) + 150 = \$830.00
Annual cost = (\$830)(0.117) = \$97.11/year

Annual energy cost with no collector

= (39,000 BTU/day)(365 days/year)(1.26×10^{-5} \$/BTU)
= \$179/year

Yearly savings = (annual energy cost)(% saved) - annual cost of solar system

For example, for one panel

yearly savings = (\$179)(.297) - 37.44 = \$15.72

$$\text{Pay off period} = \frac{\ln\left[\frac{(179)(.297)}{(179)(.297) - (.08)(320)}\right]}{\ln(1 + .08)} = 8.5 \text{ years}$$

Similar calculations were performed for 2,3, and 4 panel systems. Additionally, the cost analysis was repeated for a projected fuel cost escalation of 5%, the results of which are summarized in Table IV. As can be seen from the annual savings figures, a system of this type would not be a particularly attractive investment. This result is primarily due to the fact that circulation of water through the collector is not continuous during favorable weather conditions.

TABLE IV

Summary of Cost Analysis for Direct Circulation System

15 year lifetime - 8% interest rate

	Projected fuel cost increase %/yr	Number of panels 1	2	3	4
Initial system cost		320.00	490.00	660.00	830.00
Annual cost (In 1976 dollars)	0%	37.44	57.33	77.22	97.11
	5%	26.82	41.06	55.31	69.56
Annual savings (In 1976 dollars)	0%	15.72	21.17	10.25	- 2.33
	5%	25.68	37.44	32.16	25.23
Pay off Period	0%	8.5	8.9	11.6	15.5
	5%	6.7	6.9	8.5	10.2

II. OPEN AND CLOSED CIRCULATION SYSTEMS

A similar cost analysis procedure was performed for open and closed circulation systems. The copper collector considered in the direct system analysis was used for the open system, while an aluminum Roll Bond type was selected for the closed system analysis. In an effort to obtain a valid basis for comparison, the collector requirement for the closed system was increased by 10% to compensate for the lower overall system efficiency. The collector cost was taken to be $5 / ft^2 ($54/m^2). A summary of the pertinent variables and cost analysis results for the two systems follow:

COST ANALYSIS OF OPEN CIRCULATION SYSTEM WITH THERMAL STORAGE

Average daily insolation @ 55° tilt in Greensboro, North Carolina

$\approx$ 1500 BTU/ft^2 - day (4.73 KWH/m^2 - day)

@ 50% collection efficiency

Can collect - 750 BTU/ft^2 - day (2.36 KWH/m^2 - day)

Load (4 persons) @ 13 gal/person = 39,000 BTU/day (90° ΔT) (11.4 KWH/day)

Auxiliary energy costs @ $.0431/KWH

Pump power required @ 35' head and 5 gpm = .038 HP (.028 kw)

Mean hrs. of sunshine per year = 2767 hrs/year

Collector area = 16.2 ft^2/panel (1.5 m^2/panel)

Collector cost = \$10.50/ft^2 (\$113/m^2)

Pump cost = $50

Valves, piping, and controls = $150 (includes valves & controls for drain down)

Storage tank cost: 42 gal (159 liters) - $130.00
82 gal (310 liters) - $220.00

System lifetime = 15 yrs

Interest rate = 8% CRF = .1168

Fuel cost escalation rate = 5% $CRF_{effective}$ = .0838

Installation cost = 0

Pump power cost = [.0431 $KWHR][.038 HP][2767 hrs sunshine/year][.7457 $\frac{KWHR}{HP\ HR}$]

Annual pumping cost $\approx$ $3.50/year

SUMMARY OF COST ANALYSIS RESULTS FOR OPEN CIRCULATION SYSTEM

No. of panels	2	3	4
System collector area (ft^2)	32.4	48.6	64.8
System collector area (m^2)	3.0	4.5	6.0
% of load system carries	63%	94.5%	100%
Collector cost ($)	340	510	680
Storage required (gal)	42	82	82
Storage required (liters)	159	310	310
Initial system cost (total) ($)	670	930	1100
Annual cost 0% fuel escalation ($)	78.26	108.63	128.48
Annual cost 5% fuel escalation ($)	56.15	77.93	92.18
Annual savings 0% fuel escalation ($)	31.01	57.05	47.02
Annual savings 5% fuel escalation ($)	53.12	87.73	83.32
Pay off period 0% fuel escalation (yrs)	8.4	7.6	8.8
Pay off period 5% fuel escalation (yrs)	6.6	6.1	6.9

COST ANALYSIS OF CLOSED CIRCULATION SYSTEM (ALUMINUM COLLECTOR) WITH THERMAL STORAGE

Average daily insolation @ 55° tilt at Greensboro, North Carolina

$\simeq$ 1500 BTU/ft^2 - day (4.73 KWH/m^2 - day)

@ 50% collector efficiency can collect

$\simeq$ 750 BTU/ft^2 - day (2.36 KWH/m^2 - day)

Load (4 persons) @ 13 gal/person $\simeq$ 39,000 BTU/day (90° ΔT) (11.4 KWH/day)

Auxiliary energy cost = .0431 $/KWH

Pump power required = .038 HP (.028 kw)

Mean hrs of sunshine = 2767 hrs/year

Collector area = 16.2 ft^2 + 10% (Due to less efficient heat transfer with heat exchanger and anti-freeze solution)

= 17.8 ft^2/panel (1.65 m^2/panel)

Collector cost = \$5/ft^2 (\$54/m^2)

Pump cost = $50

Valves, piping and controls = $100 (no drain down capability)

Working fluid cost = $50

Storage tank cost = 42 gal (159 liters) = $160.00
82 gal (310 liters) = $250.00

Heat exchanger cost = $75

System lifetime - 15 yrs

Interest rate - 8%

Fuel cost escalation rate - 5%

Annual pumping cost $\simeq$ \$3.50/year

Installation cost = 0

SUMMARY OF COST ANALYSIS RESULTS FOR CLOSED CIRCULATION SYSTEM

Number of panels	2	3	4
System collector area (ft^2)	35.6	53.4	71.2
System collector area (m^2)	3.31	4.96	6.62
% of load carried by system	63%	94.5%	100%
Collector cost ($)	178	267	356
Storage required (gal)	42	82	82
Storage required (liters)	159	310	310
Initial system cost ($)	613	792	881
Annual cost 0% fuel escalation ($)	71.60	92.51	102.90
Annual cost 5% fuel escalation ($)	51.37	66.37	73.83
Annual savings 0% fuel escalation ($)	38.97	73.34	72.60
Annual savings 5% fuel escalation ($)	59.20	99.48	101.67
Pay off period 0% fuel escalation (yrs)	7.4	6.1	6.5
Pay off period 5% fuel escalation (yrs)	6.0	5.2	5.4

It should be noted that the above figures are based on average climatological data and therefore are not completely accurate. However, in computing initial system costs, an effort was made to over-estimate component costs, in hopes that the whole would present a realistic picture of the economic feasibility of a solar hot water system. The 5% projected fuel cost escalation rate is also felt to be conservative and a more attractive return is quite possible. Hopefully, proposed government tax breaks and low interest loans for solar installations will become a reality and thus further enhance the desirability of solar energy utilization.

CONCLUSIONS

As can be seen from the results of the cost analyses of the various systems considered, the closed circulation system appears to be the most attractive economically. This conclusion, however, is sensitive to several variables and practical considerations and must be viewed with reservation. For systems requiring a large collector area, for example, the reduction in collection costs with a closed system would undoubtedly outweigh the loss of system efficiency and the additional complications due to using a working fluid other than water. For systems of about 50 ft^2 (4.6 m^2) or less, the circulation system with a copper collector would probably be the most practical. A further consideration is the skill of the installer who, for example, may be able to fabricate a suitable copper or stainless steel collector at a lower cost than was used in the foregoing analysis.

Obviously, then, the selection of a basic system type must be based on the circumstances and design requirements of the particular application. It is hoped that this report will be of some aid in understanding the various options available and the factors which must be considered in making such a decision.

North Carolina State University is developing more detailed plans for both open and closed circulation systems. Hopefully, construction and performance testing of one, or both, will be possible in the near future.

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